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Research Article

Empirical evaluation of change in crash risk due to lane marking reallocation: A case study in Kochi City, Japan

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ABSTRACT

Lane markings are considered an essential component of a road system. As highlighted in previous studies, they are directly linked to efficiency and safety. The rearrangement or reallocation of lane markings can be an economical way to improve efficiency. However, such changes could influence driver behavior. Thus, there is a tradeoff between efficiency and safety. Through a case study in Kochi City, Japan, this study evaluated the change in crash risk caused by a lane marking reallocation. Video data were collected before and after the implementation of a new road layout (achieved by reallocating lane markings) that was intended to mitigate traffic congestion at a signalized intersection. Based on the video data, PICUD (Possibility Index for Collision with Urgent Deceleration), a surrogate safety index used to estimate collision risk, was estimated for lane changes and conflicts between leading and following vehicles in the through lane. In particular, it was confirmed that the collision risk between a lane-changing vehicle and a leading vehicle in the through lane was reduced due to the reduction in traffic density caused by the new road layout. In addition, the results indicate that the PICUD value tends to decrease (i.e., the crash risk tends to increase) with increasing speed of the following vehicle relative to the leading vehicle. Overall, the improvement in safety after the implementation of the new road layout was marginal and statistically insignificant. Therefore, this study highlights the necessity of incorporating speed control measures, such as speed limits, along with congestion alleviation measures in order to enhance safety.

1. Introduction

Lane markings are considered a critical design component and are a common element of a roadway system. They provide guidance for the alignment of the road, assisting drivers to correctly position themselves in a lane [1–3]. In general, lane markings delineate and define traffic lanes, which can be directly linked to efficiency and safety. Moreover, there are various types of lane markings, each with its own meaning [4]. Therefore, they communicate road information as well as rules to drivers to help them navigate roads safely and efficiently. Previous studies have demonstrated that lane markings have substantial safety benefits, including crash reduction [5–11]. Miller reported that longitudinal pavement markings and edge lines on rural highways reduce crashes by 21% and 8%, respectively [7]. A study by Hussein et al. found that wider lane markings reduced total road collisions by 12.3% and run-off-road collisions by 19.0% on Canadian roads [11]. In addition to such safety benefits, when designed appropriately, lane markings optimally distribute traffic into lanes and make roadways more efficient by reducing congestion and increasing capacity [7,12,13].

In addition to safety and efficiency, the behavioral aspects associated with lane markings have been examined. A study by Ranney and Gawron based on a driving simulator experiment found that the presence of edge lines was linked with faster speeds, particularly at the entrance of a curve [14]. However, according to a meta-analysis by Van Driel et al. [15], both positive and negative effects of pavement edge lines have been reported. Specifically, although some studies reported an increase in speed of up to 10.6 km/h, other studies reported a decrease in speed of up to 5.0 km/h. A study by Yagar and Van Aerde [16] found that the driving speed is not influenced by the addition of a centerline. A before-and-after study by Tsyganov et al. [17] concluded that even though vehicle speeds slightly increased when edge lines were introduced to narrow highways, this increment was not statistically

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significant. However, according to a recent study by Garach et al. [18], wider lane markings may create the illusion of faster movement, and this perception of higher speed may lead to speed reduction. Results on lateral position are also mixed. Even though some studies found that vehicles shift up to 30 cm towards the centerline, other studies reported a shift of 35 cm towards the edge of the road [15]. As reported in some studies (e.g., Triggs and Wisdom [19]), lane delineation markings positively affect the maintenance of vehicle lateral position. However, outcomes related to the effect of the width and contrast of lane delineation markings are mixed. For example, although McKnight et al. [20] found that the width and contrast do not have a significant effect on lane keeping, a field study by Miles et al. [21] found that wider and brighter road markings allow motorists to better position themselves in their lanes.

The change and relocation of lane markings could also have a significant influence on the safety and performance of road segments, as examined in previous studies. Retting et al. [22] studied the effect of an experimental lane marking pattern that narrowed down the lane width using a gradual inward taper on vehicle speeds on exit ramps. Results indicated that this marking pattern effectively reduced these speeds. Raimondo et al. [23] studied the influence of horizontal markings on curved exit ramps on driver safety-related performance. The results indicated that horizontal markings with internal lane bands significantly improved road safety compared to other types of marking. In addition to safety, efficiency and capacity should also be taken into account. However, these aspects were not considered in the above studies.

In general, the optimal arrangement of lanes could improve the capacity of intersections by maximizing traffic flow [12,24–26]. This implies that lane markings at intersections play a role in enhancing intersection capacity. Wong and Wong [24] presented a capacity maximization and cycle length minimization problem in a unified framework, in which traffic as well as pedestrian movements were considered. In a unified framework, Wong and Heydecker [25] optimized the lane marking patterns and signal timings at an isolated intersection. The influence of time-varying demand patterns in such optimization problems, which include the arrangement of lane marking patterns, has also been studied [26]. Shi et al. [27] proposed a method for minimizing the delay for buses and cars at an isolated signalized intersection with an exclusive bus lane and a passive bus priority signal. Their study considered lane allocation, including lane markings for both exclusive bus lanes and other traffic. In order to determine the lane markings and signal timings for signalized roundabouts, Ma et al. [28] presented an integrated optimization model. In addition to the minimization of cycle lengths and delays, the maximization of capacity was taken into account. Using vehicle trajectory data, Zheng et al. [29] jointly optimized the signal timings and lane assignments, including lane markings, at an isolated signalized intersection. The above studies highlight that the optimal arrangement of lane markings can enhance the capacity of intersections. Lane marking rearrangement or reallocation can be considered a low-cost solution [30] because it is less expensive than physical changes such as the addition of new lanes or the expansion of an intersection. It should be noted that changes to lane markings can change driver behavior [3]. Thus, there is a tradeoff between efficiency and safety; even though changing lane markings and rearranging lanes may improve the capacity or performance of an intersection or a road section, they would have a negative impact on safety. Such aspects have not been comprehensively examined in previous studies, which mainly focus on either safety or capacity.

Through a case study in Kochi City, Japan, the present study assesses the change in crash risk following the rearrangement and relocation of lane markings at a signalized intersection. Video data were collected before and after the rearrangement of lane markings. Based on the trajectory data extracted from the video data, crash risk was estimated using a surrogate safety measure. A before-and-after analysis was conducted on the estimated values.

The rest of this paper is organized as follows. Section 2 describes the site before and after the lane marking reallocation along with the crash risk estimation and analysis methods. Section 3 presents and discusses the results. Finally, Section 4 gives the conclusions.

2. Methods

2.1. Site description and background

The study site, namely the Harimayabashi intersection, is located in Kochi City, on the island of Shikoku in Japan (33° 33′ 32″ N 133° 31′ 53″ E). For the original layout (Fig. 1, left), during the morning and evening peak hours (7:00 to 8:00 and 17:00 to 18:00, respectively), the first eastbound lane functioned as a bus-only lane until just before the Sakaimachi bus stop, which is located approximately 200 m before the intersection. The third eastbound lane was a dedicated right-turn lane. Due to these conditions, heavy traffic congestion was observed in the second (middle) lane, particularly during peak hours [31]. Therefore, congestion alleviation measures were necessary. For the new layout (Fig. 1, right), a merging zone, a flow channel, and a bus bay are introduced. Furthermore, the long dedicated right-turn lane is divided into two through lanes and a shorter dedicated right-turn lane is introduced by reallocating the lane markings.

These traffic congestion countermeasures were implemented effective June 7, 2019. The Ministry of Land, Infrastructure, Transport and Tourism of Japan reported that this new layout remarkably reduced the eastbound traffic congestion at the Harimayabashi intersection and two upstream intersections. Specifically, the maximum peak-hour congestion at the Harimayabashi intersection in the eastbound direction was reduced from 180 to 80 m. Moreover, the 30 m peak-hour eastbound congestion at the Nakanohashi-dori intersection (located approximately 430 m upstream) was eliminated. The traffic lane utilization rate near the intersection in front of the Horizume tram stop (located approximately 330 m upstream) decreased by about 20% for the second lane and increased by about 30% for the third lane [32]. However, the report did not mention traffic safety.

The new road layout may actually create traffic safety issues. Before the implementation, the first lane was for buses only, and thus vehicles that used it could merge in and out of the lane rather simply. In the new layout, however, the bus bay and accompanying merge zone impede straight-ahead driving as a lane change is required whenever a merge is performed. The required through-lane merge at the end of the bus-only lane increases the frequency of lane changes, creating more potential conflicts between vehicles. In this study, it was hypothesized that after the new road layout is implemented, traffic density will decrease due to congestion mitigation and thus lane changes will be safer even though the frequency of lane changes will increase. In order to verify this hypothesis, an objective risk assessment was conducted using the Possibility Index for Collision with Urgent Deceleration (PICUD), which is a surrogate safety index proposed by Uno et al. [33]. To collect data, video surveillance was performed at several locations in the vicinity of the Harimayabashi intersection. Details of the video data collection are provided in the next subsection.

2.2. Video data collection

Video surveillance was conducted at several locations along a stretch of road using overhead video cameras before and after the implementation of the new road layout. As mentioned, the new congestion elimination plan was effective June 7, 2019. The video surveillance was conducted on two days before this date (i.e., May 30 and 31, 2019) and on two days after this date (June 10 and 14, 2019). Table 1 presents a summary of the video surveillance. The locations of the video cameras are shown in Fig. 2. To distinguish between lane-change behaviors in different sections of the road, the original section was divided into three subsections, as shown in Fig. 3. Section 1 includes lane changes due to the new merge section. Section 2 includes lane changes due to the

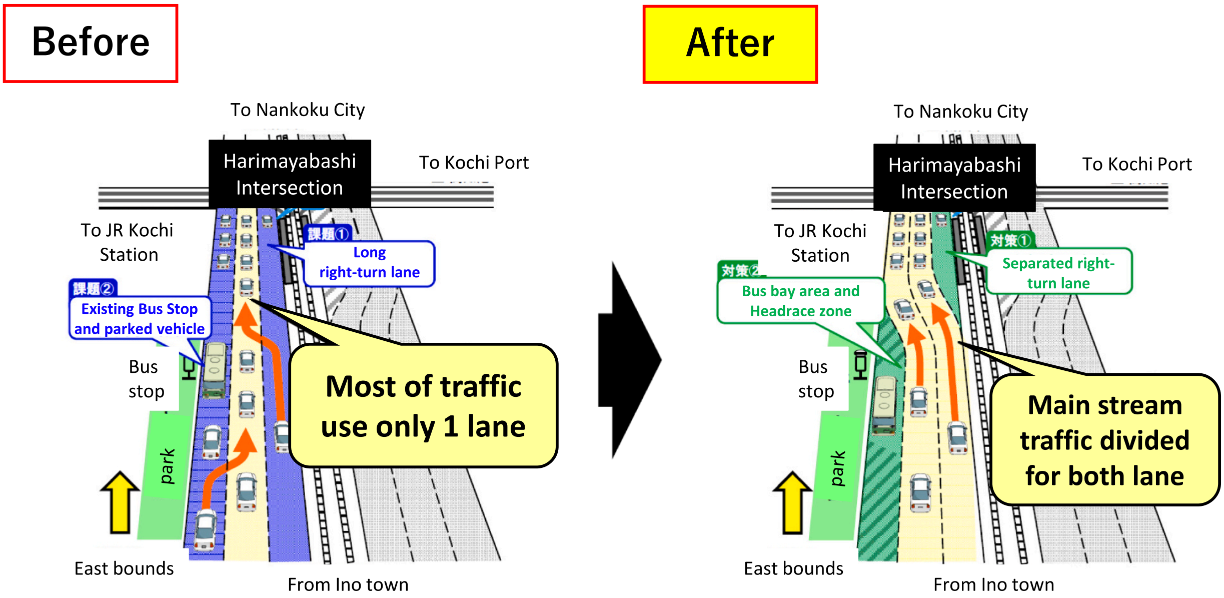


Fig. 1. Lane marking arrangements before and after implementation of congestion countermeasures (source: Ministry of Land, Infrastructure, Transport and Tourism, Japan, https://www.skr.mlit.go.jp/tosakoku/pres/2019/190826.pdf).

Table 1
Outline of traffic data collection survey.

Purpose of the survey		1. Data collection of lane changing behavior 2. Data collection for PICUD calculation 3. Data collection of traffic state	
Date	Before	30th (Thursday) and 31the (Friday) May 2019	6:30 am to 9:30 am
	After	10th (Monday) and 14the (Friday) June 2019	
Survey area		Harimayabashi Intersection to Ohashidori Intersection	
Number of camera setting		4	
Number of video camera		8	

addition of a bus-only lane. Section 3 includes lane changes due to the new bus-only lane and bus bay. Because lane changes due to the bus bay were observed for both the original and new layouts, Section 3 was used for comparing the layouts.

2.3. *Video image processing and data extraction*

The following steps were used to extract the required data from the videos.

Step 1: Extraction of images

In this study, the multimedia player GOM Player (https://www.gomlab.com/) was used (see Fig. 4). This software has an image capture function and can automatically save images at specified intervals for specified portions of the video. With the assistance of such functions, video portions corresponding to lane changes (i.e., from the start to the completion of a lane change by the target vehicle) were clipped. Then,

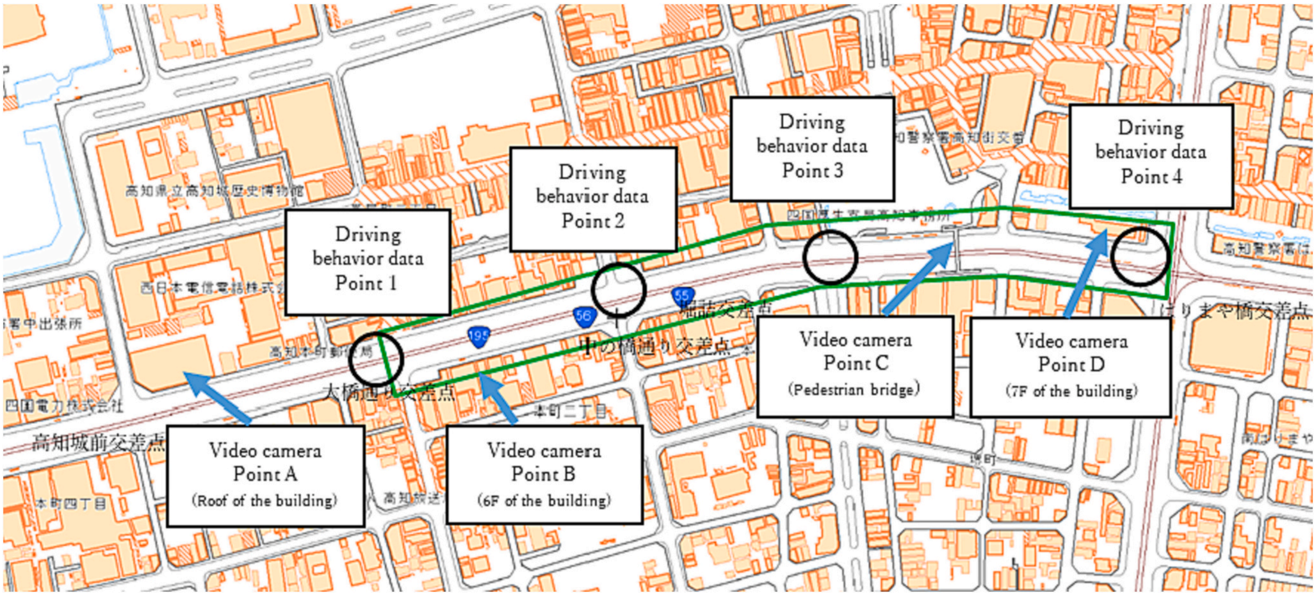


Fig. 2. Map of video camera locations and driving behavior measurement area.

Fig. 3. Definition of target sections for traffic data collection.

画面キャプチャー設定

キャプチャー画像の保存

フォーマット: JPEG

出力サイズ: 画面サイズに合わせる

画質: 255 [1 ~ 255]

連続キャプチャー間隔(秒): 0.5 [0.01 ~ 120]

☐ フレーム単位でキャプチャー

連続キャプチャーフレーム: 14 [1 ~ 999]

壁紙設定

★ 再生中の画面をデスクトップの壁紙にします。

Windowsのデスクトップ設定で"WEBコンテンツを表示"オプションが設定されている場合、この機能が動作しないことがあります。

保存設定

C:¥Users¥B302¥Desktop¥PICUD¥6.10 区間2¥

ファイル名の規則: 動画の再生時間を基準にする

☑ 連続画面キャプチャー時、動画ファイル名のフォルダーを作成

Fig. 4. Screenshot of the video playback and image extraction tool.

images were extracted at intervals of 0.5 s to obtain image sequences for each lane-change event. As information for both leading (front) and following (rear) vehicles is required to estimate PICUD, image sequences were further narrowed down to extract such cases.

Step 2: Extraction of trajectories

The image processing software ImageJ (https://imagej.en.softonic.com/) was used to track the pixel coordinates. Image coordinates (in pixels) were recorded by manually clicking on images in an imported image sequence at intervals of 0.5 s. The recorded pixel coordinate data were saved as CSV files. After the coordinates extracted at intervals of 5 m on the road (i.e., real-world coordinates; see Fig. 5) were matched to the corresponding image coordinates (in pixels), a non-linear function was obtained to convert the image coordinates into real-world coordinates. The head positions of the leading and following vehicles in the saved image sequence were tracked at intervals of 0.5 s. Fig. 6 shows an example for a situation where a lane changing front vehicle and a rear vehicle interact.

Step 3: Calculation of vehicle position, speed, and inter-vehicle distance

The coordinates acquired in Step 2 were converted into real-world coordinates using the transformation function. Using these real-world coordinates, the distance traveled and the speed at intervals of 0.5 s were obtained. The distance between the leading and following vehicles was calculated from the difference between the positions of these vehicles. The PICUD value was calculated using the extracted data. Details of the PICUD calculations are discussed in the next subsection.

2.4. Estimation of collision risk

In order to objectively assess the effect of congestion countermeasures on the collision risk of lane entry and exit vehicles, the distance-based surrogate safety index PICUD was used. PICUD is calculated as follows:

$$PICUD = \frac{V_1^2}{-2a} + s_0 - \left(V_2\Delta t + \frac{V_2^2}{-2a}\right) \tag{1}$$

where V_1 and V_2 are the speeds (m/s) of the leading and following vehicles, respectively, s_0 (m) is the distance between the leading and following vehicles, Δt (s) is the reaction delay of the following vehicle, and a (m/s^2) is the deceleration of both vehicles. In this study, Δt was

Fig. 5. Screenshot of coordinate conversion using ImageJ.

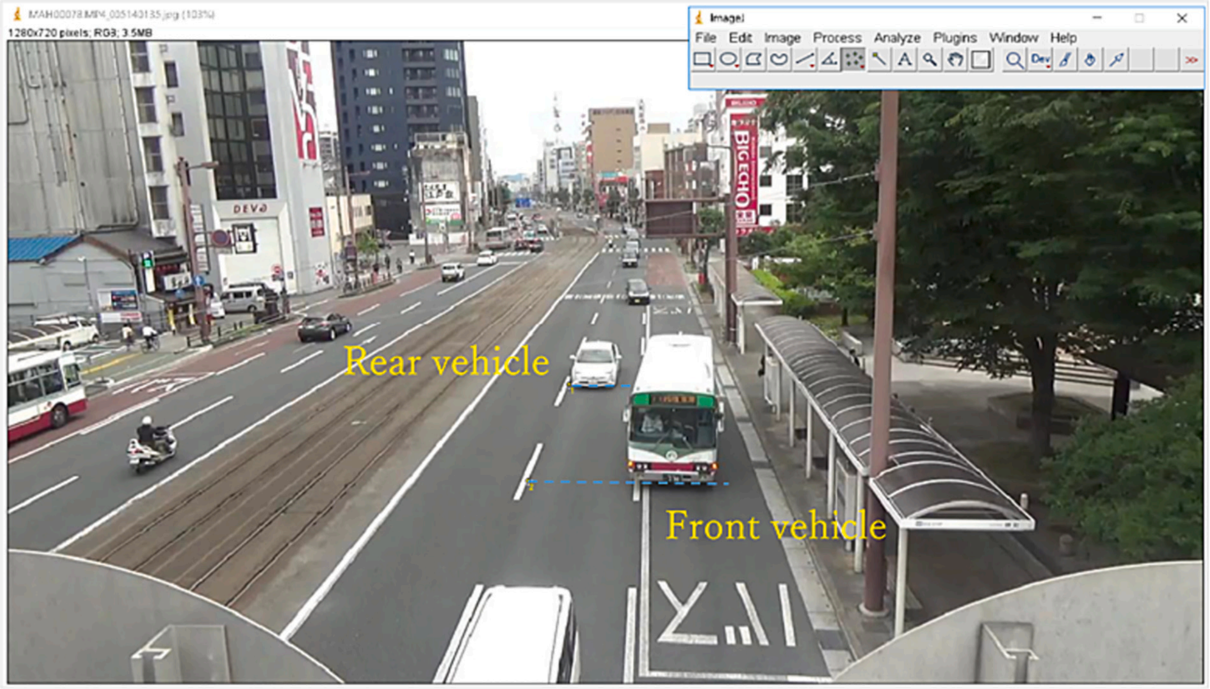


Fig. 6. Example of an interacting event where PICUD was calculated.

assumed to be 1.0 s and deceleration was assumed to be -3.3 m/s^2. These values were used based on the settings in a previous study by Suzuki and Matsumura [34] and represent near misses during sudden deceleration conditions.

The PICUD value index indicates the spacing between vehicles when the leading vehicle suddenly decelerates and the following vehicle suddenly decelerates with a reaction delay and comes to a complete stop. A PICUD value that is equal to or less than zero means that there is a risk of collision. In this case, if the leading vehicle suddenly decelerates, a collision might not be avoided even if the following vehicle also decelerates rapidly.

As mentioned, the new road layout and lane marking scheme increase the frequency of lane changes. In this study, the coordinate data were acquired at intervals of 0.5 s from the start to the completion of a lane change and the corresponding PICUD values were calculated for each interval. Cases where there were no vehicles traveling in the main lane at the time of a lane change by a vehicle entering the main lane were omitted as they have no collision risk. Cases with interacting vehicles (a vehicle in the through lane and a vehicle that is changing lanes) were regarded as a single set. The minimum PICUD value calculated from the start to the completion of a lane change (i.e., the value indicating the most dangerous scenario) was selected. In this study, two types of interaction were considered, namely (i) the interaction between a leading vehicle in the through lane and a vehicle that is changing lanes and (ii) the interaction between a following vehicle in the through lane and a vehicle that is changing lanes. In cases (i) and (ii), the leading and following vehicles, respectively, are in the through lane. Accordingly, these cases are hereafter referred to as the leading vehicle case and the following vehicle case, respectively.

The estimated PICUD values obtained before and after the implementation of the new lane marking scheme were analyzed under various conditions. The analysis results are described in the following section.

3. Results and discussion

3.1. *Characteristics of PICUD distributions*

Based on the data extracted from the videos collected before and after the implementation of the new lane marking scheme, PICUD values were calculated for both interaction types (i.e., cases with leading and following vehicles in the through lane). Table 2 summarizes the preliminary assessment of the PICUD values, that is, the number of vehicles with a risk of collision (PICUD ≤ 0). It should be noted that these data were extracted from videos that were 3 h long for each case (i.e., before and after the lane marking rearrangement). The summary of statistics listed in Table 2 indicates that, in general, there is a collision risk associated with the new road layout, particularly for sections upstream of the intersection. Furthermore, there is clear difference in collision risk among the sections. Section 1 appears to be the most critical as it has the highest percentage of cases with a collision risk (i.e., PICUD ≤ 0). Section 1 is the most upstream section of the considered stretch of road (see Fig. 3) and thus has the highest frequency of lane changes as drivers tend to adjust their lanes in response to the changed lane markings. Regarding the leading and following vehicle cases, following vehicles had higher collision risks than those of leading vehicles. This observation is logical as following vehicles in a through lane (as considered in this study) approach at higher speeds than a vehicle changing lanes from the bus lane. For Section 3, after the implementation, the collision risk decreased for the leading vehicle case and slightly increased for the following vehicle case. The mean PICUD values (± SD) were $-$ 2.90 m (± 11.79 m) and 0.45 m (± 13.89 m) before and after the implementation of the new lane marking scheme, respectively. This implies that the collision risk was reduced after the implementation; however, this reduction is statistically insignificant, as confirmed with the *t*-test ($t = -1.464$, $p = 0.073$). It should be noted that the sample sizes for the leading vehicle case for Section 3 were smaller, which might have affected the results.

Histograms representing the frequency of collision risk for Sections 1, 2, and 3 are shown in Figs. 7, 8, and 9, respectively. These figures indicate that, in general, the interaction or conflict between the lane-changing vehicle and the leading vehicle is less dangerous than the interaction between the lane-changing vehicle and the following vehicle. A comparison of PICUD values for the front or leading vehicle case for Section 3 (Fig. 9 (a)) indicates that the safety was slightly, but significantly, improved (i.e., average PICUD value decreased) after the implementation of the new lane marking scheme ($t = -2.844$, $p = 0.008$). However, as mentioned, the sample sizes were limited for this case. For the rear vehicle case for Section 3 (Fig. 9 (b)), safety was slightly improved (i.e., average PICUD value decreased); however, this improvement was not statistically significant.

Table 2

Summary of collision risk statistics for each section of road.

Target vehicle	Road section		Number of vehicles	Number of collisions	Proportion (%)
Front vehicle	Section 1		83	36	43.4
	Section 2		29	4	13.8
	Section 3	Before	27	14	51.9
		After	15	5	33.3
Rear vehicle	Section 1		73	45	61.6
	Section 2		36	24	66.7
	Section 3	Before	46	29	63.0
		After	39	30	76.9

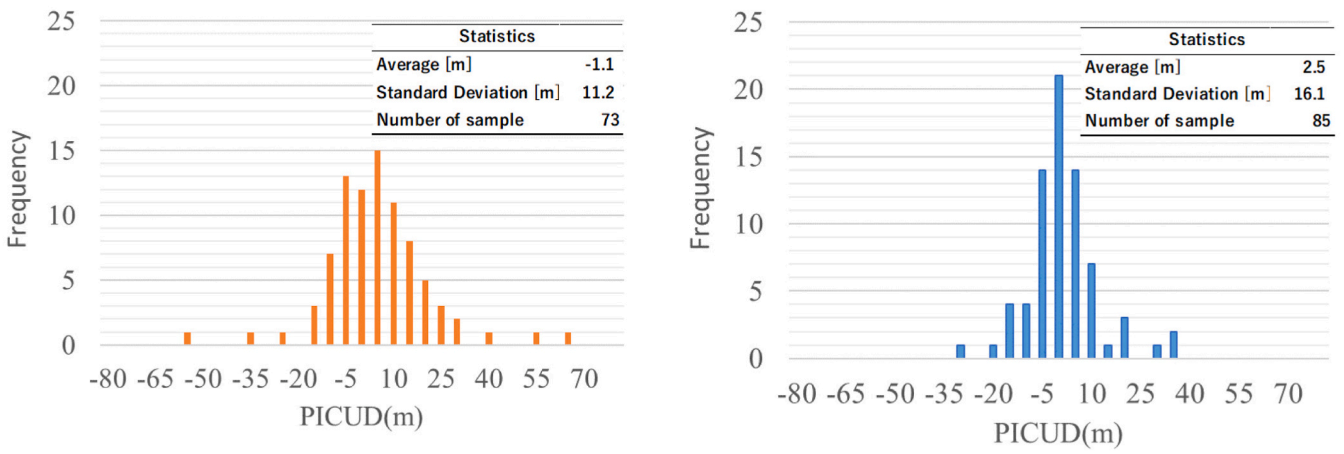
3.2. *Impact of traffic density on PICUD*

The distance-based PICUD can be highly influenced by the surrounding traffic conditions. In particular, the PICUD value is a function of the speeds of both vehicle speeds, which are, in general, affected by the surrounding traffic conditions. In this study, it was assumed that the surrounding traffic situation corresponds to the traffic density of the leading vehicle and that the degree of congestion affects lane-change behavior, which in turn influences the collision risk.

A graph of traffic density versus PICUD value for all considered road sections is shown in Fig. 10. The density of the traffic in front of the target lane-changing vehicle was used in this graph. The density observed 1 s before the minimum PICUD value was reached was used under the assumption that 1 s will elapse from the decision to change lanes to the initiation of an actual lane change. The trend of the linear regression line, which represents all sections and cases, indicates that the PICUD value decreases (i.e., the collision risk increases) when the density increases. It should, however, be noted that the PICUD versus traffic density relationship is not necessarily linear. It was noted that the (nonlinear) correlation between the density and PICUD is weak; however, it was significant at the 0.01 level (Pearson correlation $= -0.186$, $p < 0.001$). Several previous studies highlighted that the likelihood of an accident increases as traffic congestion increases [35–38]. Increased congestion means increased density, and thus the results regarding the relationship between density and PICUD obtained in the present study are consistent with earlier studies.

Based on this relationship, it can be stated that traffic density is an important factor for causal analysis in risk assessment. This means that the reduction in traffic density that results from congestion alleviation measures might improve the safety associated with lane changing despite the higher frequency of lane changes. As shown in Fig. 11, traffic density and PICUD values can be divided into four categories. The density threshold, namely approximately 40 vehicles/km, as shown in Fig. 12, that divides the categories can be considered reasonable. Assuming that low traffic density should result in high PICUD values (and thus safety), it can be predicted that a mainly negative correlation data distribution corresponds to Categories 1 and 3. In Category 1, high traffic density implies a zone with difficult lane changes and thus predicts risky lane changing. Furthermore, this state may presumably be found before the implementation of congestion alleviation measures. The low density in Category 3 defines a zone with easy lane changes and predicts safe lane changing. This state can be considered the desired state after the implementation of congestion alleviation measures.

For Category 2, a negative correlation between the density and PICUD value was observed. It agrees with the overall trend but it is weak and statistically insignificant (Pearson correlation $= -0.073$, $p = 0.63$). In contrast, for Category 4, a positive correlation was observed; however, it is also statistically insignificant (Pearson correlation $= 0.107$, $p = 0.3$). These statistics indicate that for Categories 2 and 4, other factors, such as speed variation and driver decisions, could have more influence than does density. It can further be considered that drivers managed to interact safely during lane changes (since PICUD >0) even though the density was high and the lane changing was relatively difficult. In contrast, Category 4 can be considered the most unsafe case as the speed



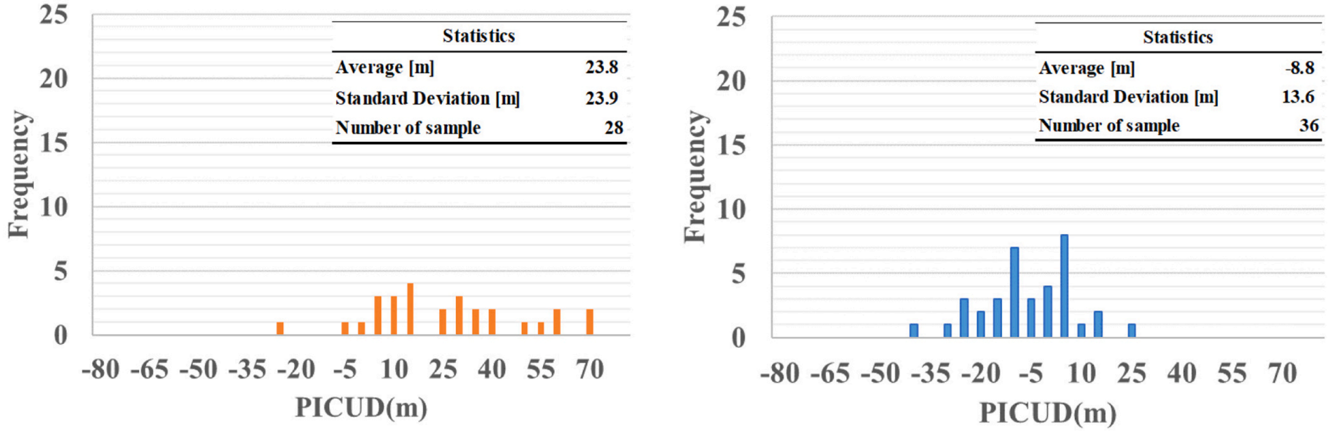
(a)

Statistics	
Average [m]	-1.1
Standard Deviation [m]	11.2
Number of sample	73

(b)

Statistics	
Average [m]	2.5
Standard Deviation [m]	16.1
Number of sample	85

Fig. 7. PICUD frequencies for Section 1 for (a) leading vehicle and (b) following vehicle.



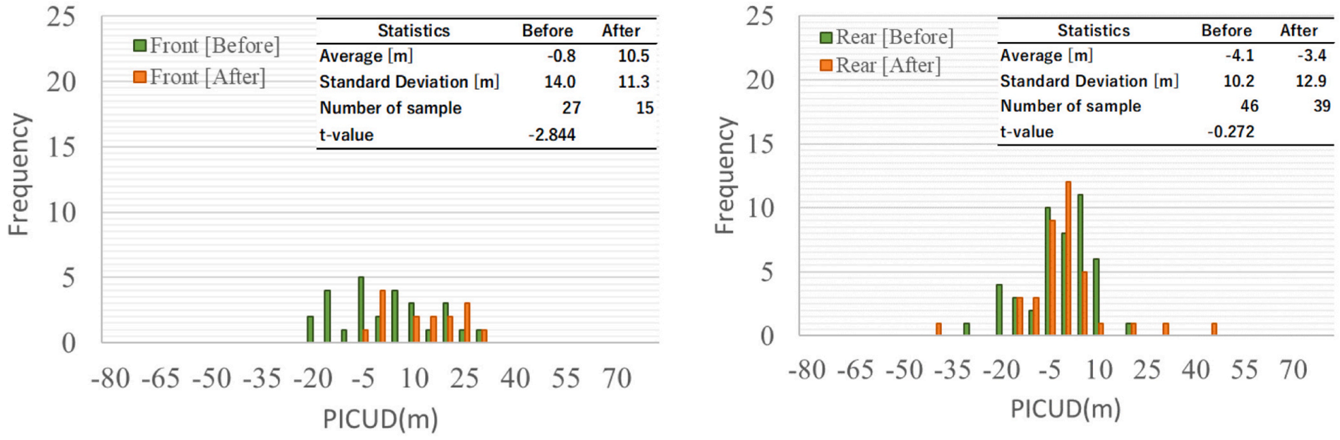
(a)

Statistics	
Average [m]	23.8
Standard Deviation [m]	23.9
Number of sample	28

(b)

Statistics	
Average [m]	-8.8
Standard Deviation [m]	13.6
Number of sample	36

Fig. 8. PICUD frequencies for Section 2 for (a) leading vehicle and (b) following vehicle.



(a)

Statistics	Before	After
Average [m]	-0.8	10.5
Standard Deviation [m]	14.0	11.3
Number of sample	27	15
t-value	-2.844	

(b)

Statistics	Before	After
Average [m]	-4.1	-3.4
Standard Deviation [m]	10.2	12.9
Number of sample	46	39
t-value	-0.272	

Fig. 9. PICUD frequencies for Section 3 for (a) leading vehicle and (b) following vehicle.

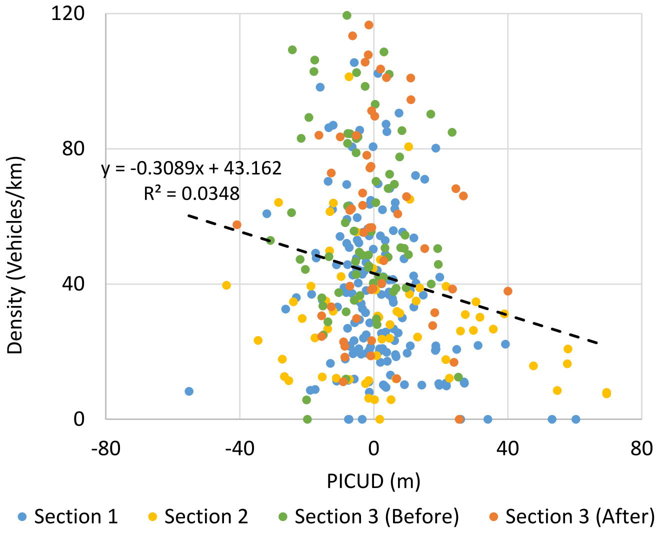


Fig. 10. Relationship between traffic density and PICUD.

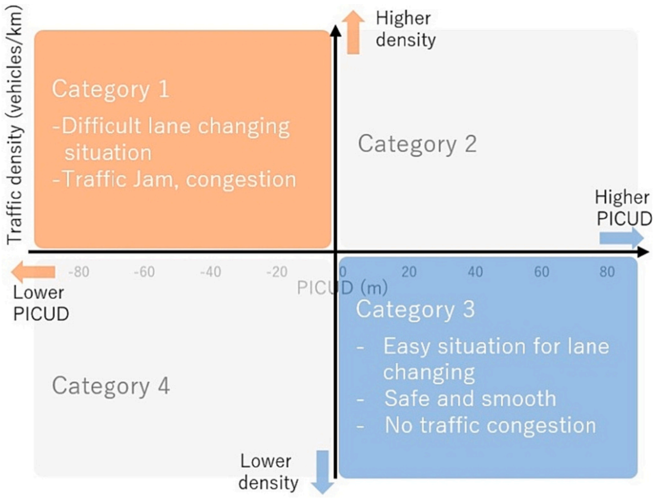


Fig. 11. Explanation of relationship between traffic density and PICUD.

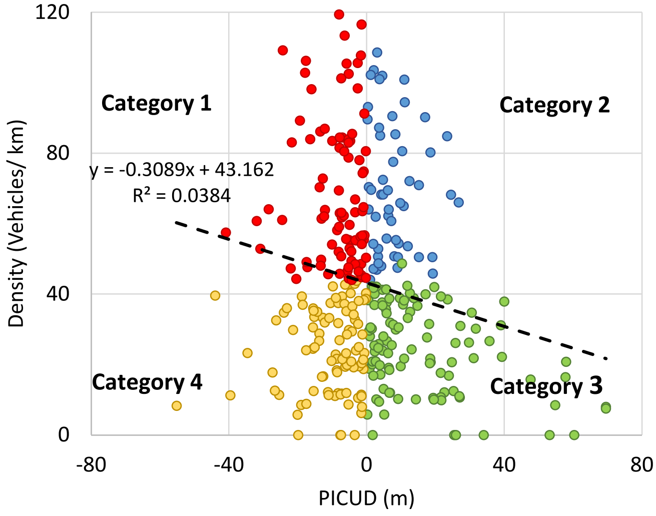


Fig. 12. Density versus PICUD corresponding to PICUD categories.

might have a significant influence. Such aspects are verified in the next subsection.

3.3. Relation between relative speed and PICUD

The relationship between relative speed (between the lane-changing vehicle and the vehicle in the through lane) and PICUD is examined in this section to clarify the interactions in Categories 2 and 4 that could not be explained by density. Furthermore, PICUD is a function of the speeds of the interacting vehicles. Thus, the relative speed between interacting vehicles should influence PICUD. In this study, since the PICUD values that correspond to lane-changing events were used, it is expected that the speed variation of the lane-changing vehicle will be higher than that of the vehicle in the through lane. Furthermore, as the leftmost lane was mainly a bus lane before the layout change and a lane with a bus bay after the change, in general, the speeds of vehicles in that lane are lower than those of vehicles in the through lanes.

Relative speed here refers to the difference between the speeds of the lane-changing and through-lane vehicles (i.e., speed of following vehicle speed minus speed of leading vehicle). Thus, a positive relative speed means that the speed of the following vehicle is higher than that of the leading vehicle, which is presumed to pose a risk of collision. A negative relative speed means that the following vehicle speed is lower, and therefore the situation is relatively safe. Fig. 13 shows the relationship between PICUD and relative speed for the four categories described in the previous section.

As can be seen, there is a strong negative and statistically significant correlation between relative speed and PICUD (Pearson correlation $= -0.733$, $p < 0.001$). That is, the PICUD value decreases with increasing relative speed. In particular, a positive relative speed (i.e., a higher speed of the following vehicle), corresponds to a negative PICUD value and thus collision risk. Accordingly, the risk of collision is higher if the speed of the following vehicle is higher than that of the leading vehicle. This outcome is logical. It is noted that the relative speed is proportional to the PICUD value, with no exceptions for any of the defined categories of state or event. However, each of the categories was found to exhibit a distinctive distribution tendency. In Category 2, in which the traffic density is high and the relative velocity is negative, the PICUD values are mostly positive (indicating safety). This could be due to the fact that it is difficult for both lane-changing and through-lane vehicles to accelerate due to congestion. In Category 4, in which the traffic density is low and the relative velocity is positive, the PICUD values are negative (indicating danger). This is because a lower traffic density makes it easier for

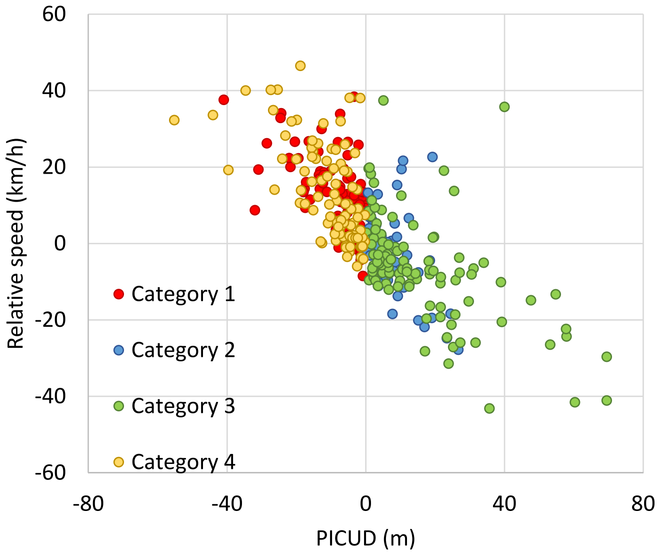


Fig. 13. Relation between relative speed and PICUD.

the driver to increase speed when changing lanes. Previous studies by Gettman and Head [39] on surrogate safety measures have also highlighted that speed and a change in speed (speed differential) could significantly affect vehicle conflicts and their severity. According to a review of studies on the relationship between driving speed and crash risk by Aarts and Van Schagen [40], higher crash rates are related to greater speed differences between vehicles, which is in line with the findings of the present study. Their review further highlighted that the crash rate increases with increasing speed and that this relationship can be described with power and exponential functions. As shown in the present study, reduced congestion due to a new road layout could increase the speed and speed difference between interacting vehicles. Intuitively, the speed of the vehicle in the through lane is higher than the speed of the lane-changing vehicle, particularly because the leftmost lane in this study is used as a bus lane. Therefore, reducing the speed of vehicles in the through lane could reduce the speed difference between the lane-changing vehicle and the through-lane vehicle. These discussions highlight the necessity of implementing speed control measures along with congestion alleviation measures in order to enhance safety. Speed limit measures can be recommended to reduce the speed of vehicles approaching intersections, for example, by lowering the speed limit (30-40 km/h) at upper streams of road sections from 50 km/h, which is the current limit for all road sections in the study site. In addition to the new speed limits, new signage and enhanced road markings can also be introduced to guide the drivers. Previous studies have also explained that the enhanced markings on the roads improve drivers' confidence in their ability to drive safely [9].

4. Conclusions

Based on a case study in Kochi, Japan, this study investigated the change in crash risk following the implementation of congestion alleviation measures. A new road layout was implemented, primarily by reallocating the lane markings, at the Harimayabashi intersection, which is a busy intersection located in the heart of the city. Before and after the new road layout was implemented, video surveillance was carried out. Using the collected video data, PICUD values were estimated for the interactions between the lane-changing vehicle and the vehicle in the through lane at three locations of the considered stretch of road.

The results indicate that the safety was slightly improved (i.e., the PICUD value was increased and became positive), after the implementation of the new lane marking scheme. For the leading vehicle case, the average PICUD value was significantly increased, indicating that safe lane changing could be achieved for the lane-changing vehicle when there is a leading vehicle in the through lane after the reallocation of lane markings. The association between traffic density and PICUD values indicates that high traffic density may be dangerous because it makes lane changes difficult. On the other hand, safe lane changes can be made with low traffic density. However, when traffic density is low, the approaching speed of the following vehicle in the through lane could be higher than that of the lane-changing vehicle, which could pose a collision risk.

The new road layout implemented at the Harimayabashi intersection was effective in reducing congestion and improving capacity, as highlighted by the road authorities. Regarding safety, the outcomes of this study partially support the congestion alleviation measures by showing that lane-changing maneuvers are safe only for leading vehicles that interact with lane-changing vehicles. For following vehicles that interact with lane-changing vehicles, a higher collision risk was identified. In addition, for some sections, the outcomes were consistent with the hypothesis that traffic density will decrease due to the reduction in congestion after the new lane marking scheme is implemented. Thus, even if the frequency of lane changes increases, safe lane changes could be achieved in upstream sections. On the other hand, it was found that a decrease in traffic density could increase speed, potentially increasing the risk of collision. This means that even if the traffic density decreased, there is still a risk of collision during lane changes.

In summary, this study demonstrated that decreasing traffic density (by implementing congestion alleviation measures) creates an environment where the speeds of vehicles in the through lane could increase, which creates a new risk scenario. This indicates that, in order to ensure safety, appropriate speed limits should be implemented along with congestion alleviation measures. Appropriate speed limits could control the speed of vehicles in the through lanes, reducing the relative speed between the lane-changing vehicle and the vehicle in the through lane. It should be noted that, in general, the speeds of vehicles in the bus-only lanes are relatively low.

This study has several limitations. In the PICUD calculations, the same deceleration ($-3.3\ \mathrm{m/s^2}$) was assumed for both vehicles, even though the deceleration may differ between the leading and following vehicles. Thus, more representative values should be used in future studies. Furthermore, the PICUD values were extracted from video recordings that were 3 h long. Therefore, the sample sizes were limited for some cases. In addition, for the after-implementation case, the data extracted from the videos obtained just after the implementation of the new lane markings were used. Familiarity with the new road layout might impact the outcomes and thus some additional video data might be needed to verify the observed effects. The combined effects of lane marking reallocations on safety and efficiency may be explored through both statistical and simulation models in future studies. Such models can be calibrated and verified using the empirical data presented in this study.

CRediT authorship contribution statement

Hiroaki Nishiuchi: Conceptualization, Methodology, Supervision, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Charitha Dias**: Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Satsuki Kawato**: Methodology, Software, Data curation, Formal analysis, Visualization.

Declaration of Competing Interest

The authors declare no conflict of interest.

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